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Facing climate change-related extreme events in megacities of China in the context of 1.5 °C global warming

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Studies on the effects of 1.5 °C global warming above pre-industrial levels, especially in megacities, are very limited. Here, we review recent progress in understanding climate change-related extreme temperature and precipitation events in China's megacities, and provide some potential options for adaptation. Studies have indicated that both global warming and urbanization could strengthen heatwave and extreme precipitation events. These extreme events have shown an uptrend in China's megacities and are projected to further increase in the future. Notably, the projected intensity of extreme temperature and precipitation events in China's three urban agglomerations is lower under 1.5 °C global warming compared with 2 °C. Furthermore, adaptation options to cope with the increasing risks of extreme weather and climate events are crucial for megacities due to the combined effects of global warming and urbanization.

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Introduction

Since 1950, many extreme weather and climate events have increased in frequency and intensity in most parts of the world [1,2] — particularly, heatwaves and heavy precipitation events [3]. In addition, the climate in large cities is also influenced by urbanization activities. Urban areas are recognized as the 'first responders' to climate change in terms of adaptation and mitigation [4]. Over half of the world's human population lives in urban areas and the bulk of global economic productivity originates from cities [5]. Some recent studies have indicated that extreme temperature and precipitation events have shown a substantially larger increase in frequency and intensity in urban areas compared with rural areas [6,7]. The occurrence of such types of extreme weather events in cities could lead to serious damages and economical losses, and even loss of human lives.

China has experienced rapid development over the past few decades, especially in megacities. Among the megacities in China, Beijing, Shanghai, Guangzhou, Hangzhou, Nanjing, and Hong Kong have received the most attention. These first-tier cities are not only areas with dense populations, but also economic and cultural activity centers. In recent years, frequent extreme weather and climate events in China's megacities have resulted in disastrous consequences [8]. For instance, on 21 July 2012, the capital city (Beijing) was hit by an extreme rainstorm, which resulted in 79 deaths, the collapse of 10 660 houses, and direct economic losses of $20 billion [9]. In summer 2013, eastern China experienced a long-lasting and widespread heatwave, affecting more than half a billion people [10]. Large cities, such as Nanjing and Shanghai, were affected more seriously due to the additional impact of urban heat island effects.

So far, limited attention has been paid to the different impacts on urban areas of a 1.5 °C versus a 2 °C global warming above pre-industrial levels, especially in China. Here, we review the literature on observed changes in extreme weather and climate extremes, including urban heatwaves, and extreme temperature and precipitation events, in China's six megacities. Their projected future changes in the context of 1.5 °C global warming, compared with 2 °C, are discussed. Furthermore, possible adaptation options for climate change-related extremes in large cities are outlined.

Observed changes in extreme weather and climate events in China's megacities

Over the period 1981–2013, the observed mean surface air temperature in China exceeded the warming rate for global average [11]. Since 1950, multiple types of extreme weather and climate extremes, such as heatwaves and rainstorms, have been increasingly recorded in China.

The warming trend of extreme maximum temperature (TXx) (the abbreviations used in the text are the climate change-related extreme indices defined by the Expert Team on Climate Change Detection and Indices, for which detailed definitions can be found at http://etccdi.pacificclimate.org/list_27_indices.shtml) for China during 1961–2010 is 0.17 °C 10 a^{-1} [12]. Notably, extreme temperature events have significantly increased in China's large cities [13]. Since 2000, frequent heatwaves have occurred in Hangzhou, with long duration, broad extent, and strong intensity [14]. In Nanjing, the duration and average of maximum temperatures both accelerated during 1951–2013, and heatwaves became increasingly prevalent [15]. In Shanghai, the linear trend of heatwave magnitude was 0.06 °C 10 a^{-1} during 1873–2013, but reached 0.96 °C 10 a^{-1} during 1991–2013 [16].

In the context of climate warming, a significant uptrend in the frequency of extreme precipitation events has been observed over most regions in China [17]. In the Yangtze River Delta urban agglomeration, the numbers of both precipitation days and heavy precipitation events have shown an obvious increase. Other precipitation extreme indices, such as total precipitation on very wet days (R95p) and maximum five-day precipitation (Rx5day), have also shown increasing trends since the mid-1950s [18]. In the Pearl River Delta urban agglomeration, an uptrend in the intensity and frequency of precipitation extreme events has been reported [19]. Wong *et al.* [20] revealed that the extreme rainfall amount and its contribution to annual rainfall in Hong Kong has increased significantly. In Guangzhou, a study indicated that the number of rainstorm days is highly positively correlated with the number of rainfall days, which has significantly increased in South China [21].

Urbanization has also contributed to local climate changes through rapid increases in the built-up infrastructure, land-use cover change, and massive emissions of greenhouse gases and aerosols [22]. As a result, the urbanization effect may partly contribute to the frequency and intensity of extreme weather and climate events in city areas. In Nanjing, extreme hot events occur most frequently in the urban area, with the daily maximum (minimum) temperature exceeding 36 °C (28 °C) on around 40% (32%) of days [23]. In Hangzhou, the urban heat island effect has caused intensification of extreme heat stress [24]. In recent years, haze pollution in China's cities has become increasingly serious due to increasing anthropogenic emissions [25•]. New studies have indicated that the biogeochemical effect of urban aerosols and haze pollution could also contribute to the urban heat island effect [26••].

Furthermore, the temperature changes in megacities are related to at least three aspects: global warming background, location/latitude, and urbanization level. Due to limitation of the observed data and attribution studies, it is hard to tell what part of temperature increase was caused by the global warming and what part remained for the intensification of the UHI in these megacities. To quantify the contribution, one of the possible way is to use numerical model. For example, Sun *et al.* [27••] performed attribution analyses and detected that nearly one-third of the observed warming rates during 1961–2013 were due to urban warming effects. In more detail, the contribution of urban warming to the background warming in three representative cities — Beijing, Shanghai, and Guangzhou — is 12.7%, 29.0%, and 23.6%, respectively [28].

The increase in extreme precipitation events in large cities is considered to be due to land-use cover change and air pollution [22,29]. In the Pearl River Delta urban agglomeration, heavy precipitation and lightning frequency are highly correlated with air pollution levels during 2000–2007 [22]. On a local scale, Jin *et al.* [29] suggested that urban canyon-lifting, aerosols, and urban heat island effects all enhanced the extreme rainstorm on 21 July 2012 in Beijing. Moreover, it has been shown that there is an increased likelihood of extreme precipitation in Shanghai's urban center region [30]. Recent related research has indicated that the contribution of heavy rainfall to the total precipitation in summer in the Beijing urban area has increased compared with the suburban area since 2004 [31]. For Guangzhou, the occurrence of heavy rainfall in the urban and downwind region has also been found to be greater than in other areas [21].

Projected extreme weather and climate events in China's megacities

Some extreme weather and climate events are projected to increase in the future. Specifically, in the upcoming two decades, 50% of summers will be hotter than the record-breaking 2013 summer, even under representative concentration pathway RCP4.5 — the moderate emissions scenario [10]. Based on statistical downscaling of 26 datasets of global climate model projections, Lee *et al.* [32] indicated that extremely high temperature events will be more frequent in Hong Kong, and the average annual number of very hot days is expected to increase from 9 days in 1980–1999 to 89 days in 2090–2099. In Beijing, based on a multi-model ensemble mean, the projected hot spell duration in the 2090s under the RCP8.5 scenario is 4.3 days per year, while it is only 1.7 days per year during 1960–2005 [33]. A recent study also revealed that the same forcing would lead to more extreme hot summers in China than the global average [34].

Global warming will also intensify regional hydrological cycles, and thus may lead to an increase in extreme precipitation events in the future, especially in most river basins in southeast China [35]. In the Huaihe River basin,

the high flood risk area during 2010–2040 is projected to be 9.95% higher compared with 1960–1980 (from 17.68 to 27.63%) [36]. Simulation results have indicated that precipitation with a return period of 20 years and 50 years in the middle reaches of the Yellow River, middle and lower reaches of the Huaihe River, and the plain area of the southern Haihe River, will even increase by more than 30% [37]. It should be noted that some large cities are located in these vulnerable river basins. Annual mean precipitation over China is likely to increase throughout the 21st century, with larger changes in precipitation usually observed in summer, and projected precipitation changes in southeast China apparently higher than in other regions [38].

Recently, the impacts of 1.5 °C warming have received attention in the scientific literature [39,40••]. Research has suggested that heat extremes and heavy precipitation extremes (such as TXx, R95p) are expected to increase in a 1.5 °C and 2 °C warming world over most parts of the globe, and a reduction of 0.5 °C (from 2 °C to 1.5 °C) results in significant decreases in projected temperature and precipitation extremes in most regions [40••,41••], including China [42]. It has been reported that the number of heatwave days, averaged for China, are 8.6 and 5.4 days per year for the 2 °C and 1.5 °C warming levels, respectively [43]. Meanwhile, the country-averaged Rx5day and fraction of R95p will increase by 5.1 mm and 6.6%, respectively, at the 2 °C warming level [44]. Furthermore, Wang *et al.* [45] showed that aerosol changes on the regional scale can outweigh the differences between 1.5 °C and 2 °C global warming.

For China's three urban agglomeration areas (UAs), the impacts of 1.5 °C and 2 °C global warming on some key extreme indices are also provided here. They are derived from 20-year time slices with the respective mean warming for each model [46]. Results indicate that TXx and R95p under 1.5 °C and 2 °C warming in China's UAs are projected to be greater than those of the reference period 1986–2005, which is 0.6 °C warmer than pre-industrial levels (1850–1900) [3]. A reduction in the global warming level from 2 °C to 1.5 °C decreases the projected TXx by about 0.6, 0.7, and 0.5 °C and the projected R95p by about 8.7, 18.6, and 6.7% in the Bohai Ring urban agglomeration, the Yangtze River Delta urban agglomeration, and the Pearl River Delta urban agglomeration, respectively (Figure 1). This suggests that China will face more severe extreme weather and climate events in these megacities. In addition, urbanization effects, such as local land use and pollutant emissions, may also further influence the local climate. Thus, China's large city areas will face greater threats in the future.

Obviously, further exploration and assessment to deliver more sophisticated knowledge on extreme events is needed, especially of global warming — and urbanization-related effects on extreme events in large cities. At present, to quantify the 1.5 °C warming effect, both high atmospheric resolution and large model output, especially for studies of 1.5 °C warming, are needed. In addition, the complexity of studies on the combined effects of urbanization and global warming on extreme events in large cities must be improved, especially those involving numerical models. It would be highly desirable for future, higher-resolution urban models to incorporate local anthropogenic changes and different aerosol compositions to reflect the additional contribution of anthropogenic effects.

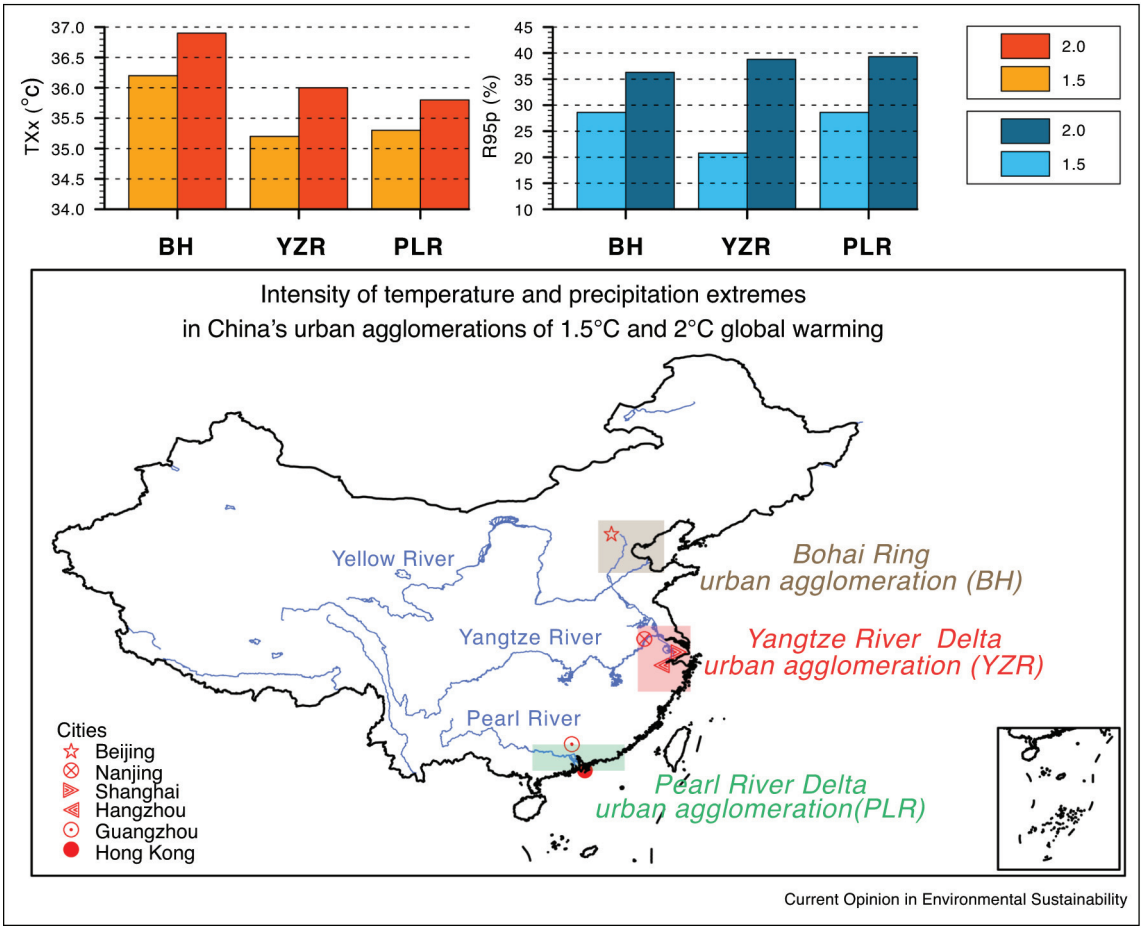
Strengthening responses to climate change-related extremes in large cities

Denser populations, busier transportation, and increasing outdoor activities in large cities result in urban-based people being more vulnerable and exposed to extreme events, such as heatwaves and extreme heavy precipitation. In response to the increasing impact of climate change on cities, mitigation measures such as the development of a low-carbon economy [47], advancement of urban ecological development [48], and energy structure improvements [49], are essential. As mentioned above, a reduction in the warming level of 0.5 °C decreases the projected intensity anomalies of extreme temperature and precipitation events. Notably, even under 1.5 °C global warming, extreme events are projected to increase relative to 1986–2005 based on the above results. In addition, urbanization will enhance the impact of global warming on extreme weather and climate events in China's large cities and cause an increase in direct economic losses. Therefore, as well as mitigation measures, the following adaptation options are also crucial for risk reduction.

(1) **Strengthening the construction standard of city infrastructure.** The design and build criteria for urban buildings, transportation, water supply, drainage, and energy facilities in cities should be improved on the basis of currently available information and estimates about extreme events [50]. Adopting thermal insulation and implementing intelligent urban design to keep buildings cool inside and improving the ventilation of urban space are important options for adaptation to heatwave events in large cities [51]. In addition, using waterproofing material and improving drainage system design to make buildings and infrastructure flood-proof are effective choices for reducing extreme precipitation-related waterlogging in cities [52]. Significantly, under the different global warming levels, distinct spatial patterns exist, resulting in regional and local extremes. Therefore, region-specific adaption strategies are also essential [53].

(2) **Increasing urban green infrastructure and enhancing the infiltration capacity of urban surfaces.** Green

Figure 1



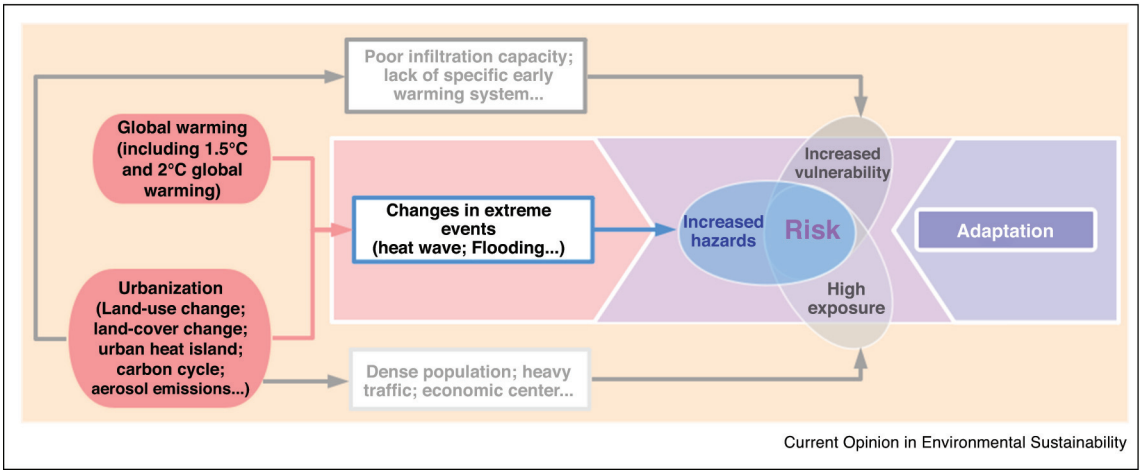
Multi-model ensemble means of TXx (extreme maximum temperature) and R95p (total precipitation of very wet days) at 1.5 °C and 2 °C warming levels under RCP4.5 in three urban agglomeration areas: the Bohai Ring (BH), the Yangtze River Delta (YZR), and the Pearl River Delta (PLR). The results are calculated from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset, which contains downscaled data from 19 CMIP5 models and is bias corrected. The 19 CMIP5 models are ACCESS1-0, BCC-CSM1-1,BNU-ESM, CESM1-BGC, CCSM4, CESM1-BGC, CNRM-CM5, CSIRO-MK3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, MPI-ESM-LR, MPI-ESM-MR and NorESM1-M. A detailed description of the model data and method can be found in Yu *et al*. [46] and detailed definitions of the extreme indices can be found at http://etccdi.pacificclimate.org/list_27_indices.shtml. Expansions of the model acronyms are available at http://www.ametsoc.org/PubsAcronymList.

infrastructure, such as green urban areas, trees, and green walls and roofs, should be increased to cool the surface temperature and reduce the effects of heat-waves [54]. Using permeable green spaces and limiting the impervious area outside and inside cities is vital to enhance infiltration and the moisture holding capacity, and can help improve the flood-resistance ability [55]. For old cities, comprehensive transformation is need — reasonably boosting the number of green and vegetation areas can lead to lower exposure and better air quality [56].

(3) **Improving early warning and emergency response capacities for extreme weather and climate events**. Using the advantages of online social network analysis and sharing of information can help provide the public with early warnings of extreme weather and climate events [57]. Combining extreme weather and climate event monitoring, forecasting, and impacts to form an integrated climate service system can help improve emergency response guidance [58]. In addition, through the organization of various forms of publicity and education activities and construction of a climate change adaptive education base, popularizing risk knowledge of extreme weather and climate events can help to enhance public awareness of climate change [59].

Fortunately, some adaptive measures have already been implemented to reduce the risk of extreme events in large

Figure 2


Poor infiltration capacity; lack of specific early warming system...
Global warming (including 1.5°C and 2°C global warming)
Changes in extreme events (heat wave; Flooding...)
Urbanization (Land-use change; land-cover change; urban heat island; carbon cycle; aerosol emissions...)
Dense population; heavy traffic; economic center...
Increased vulnerability
Increased hazards
Risk
High exposure
Adaptation
Current Opinion in Environmental Sustainability

Framework for connecting global warming and urbanization impacts on extreme events in megacities, linking the issues of exposure, vulnerability, and adaptation. Those grey-colored contents are not discussed in our present paper but are need to future further study.

cities. For instance, in China, a 'Sponge City Pilot Program' is being undertaken [60•] to maximize water retainment, minimize the impacts of heatwaves, drought and flooding, and efficiently use water supplies and reserves. In addition, an urban adaptation plan for climate change has been put forward, which clearly emphasizes the need to promote construction of urban green facilities. Through evaporative cooling and natural water infiltration, urban green facilities can help to reduce the impact of heatwaves and flooding [61]. In Shanghai, the metropolitan area has been divided into 14 water conservancy zones, which include 348 polder areas with 2517 km of dykes, 1499 pump stations, and 2203 sluices, to protect against flooding and waterlogging caused by extreme heavy precipitation [30].

Conclusions

Increasing numbers of extreme weather and climate events have been observed worldwide in recent decades. Owing to the combined effects of global warming and urbanization in China's large cities, more frequent and more serious extreme temperature and precipitation events have been recorded (Figure 2). Obviously, extreme events can cause heavy damage and economic losses, impacts to human health, and even result in the loss of human lives, especially in megacities (such as Beijing, Shanghai, and Guangzhou), which contain high densities of people and vital infrastructure. In addition, extreme events are projected to further increase in the future. However, the projected intensity anomalies of extreme temperature and precipitation events are lower under 1.5 °C global warming compared with 2 °C in the Bohai Ring urban agglomeration, Yangtze River Delta urban agglomeration, and Pearl River Delta urban agglomeration by about 0.6, 0.7, and 0.5 °C, and about 8.7, 18.6, and 6.7%, respectively. Adaptation options, such as strengthening the construction standards of city infrastructure, increasing urban green space and infiltration capacity, and improving early warning and emergency response capacities, will be very useful in response to the increasing risk of extreme weather and climate events in cities. Some important adaptation measures are already being undertaken in China.

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